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Real-time measurement of pelvis and trunk kinematics during treadmill locomotion using a low-cost depth-sensing camera: A concurrent validity study

Short Communication

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Abstract

There is currently no suitable kinematic system for a large-scale prospective trial assessing risk factors of musculoskeletal disorders. A practical kinematic system is described which involves the use of a single low-cost depth-sensing camera for the real-time measurement of 3-dimensional linear and angular pelvic and trunk range-of-movement (ROM). The method is based on the creation and processing of dynamic point clouds taken from the posterior surface of the pelvis and trunk. Nine healthy participants performed 3 trials of treadmill locomotion when walking at self-selected speed (3.6-5.6 km/h), running at 70% (10.9-14.0 km/h) and 90% of maximal speed (14.0-18.0 km/h). Stride-by-stride linear and angular ROM data were captured concurrently using the single depth-sensing camera running at 30Hz (Kinect^{TM} for Windows, Microsoft, USA) and a six-camera motion capture system at 100Hz (Vicon MX13, Vicon Motion Systems, United Kingdom). Within subject correlation coefficients between the practical and criterion method ranged from very large to nearly perfect ($r = 0.87–1.00$) for the linear ROM. Correlation coefficients for the angular ROM ranged from moderate to very large ($r = 0.41–0.80$). The limits of agreement between the two systems for linear movements was $\leq$ 9.9 mm at all velocities of gait and $\leq$ 4.6 degrees at all velocities of gait. The single camera system using depth-sensing technology is capable of capturing linear pelvic and trunk ROM during treadmill locomotion with reasonable precision when compared to the criterion method. Further improvements to the measurement of angles and validation across a wider population are recommended.

1. Introduction

Biofeedback is an emerging tool in the management of injuries in at-risk groups. When a biomechanical risk factor can be quantified and displayed to the participant it is possible to address the underlying biomechanical problem (Crowell and Davis, 2011). The quantification of risk factor variables requires a prospective study in which measurements are made in injury-free participants at baseline, thus allowing modelling to take place in the follow-up period. The strength of such statistical models depends on the number of injury events occurring in the follow-up period. Hence, large-scale baseline trials are a prerequisite even when considering the more common musculoskeletal injuries (e.g. iliotibial band syndrome).

The pelvic and trunk regions form the proximal end of the lower kinetic chain and are routinely assessed due to their reputed relationship with pelvic, spinal and lower limb pathologies (Liebenson, 2004; Sahrmann, 2002; Herrington, 2011). The surrounding core musculature provides the control and stabilization necessary for efficient gait with abnormal linear and/or angular oscillations of the pelvic and trunk regions during gait being implicated in, or symptomatic of, many musculoskeletal conditions (Saunders et al., 2005). An accessible, valid and real-time method of kinematic analysis for quantifying pelvic and trunk movements may therefore be a useful tool in injury research (Vieira and Kumar, 2004; Dutta, 2012). To date several studies have presented protocols to quantify pelvic movements during gait (Schache et al., 2002a; Schache et al., 2000). However, these are lab-based and time-consuming in terms of preparation, collection and analysis and restricted to relatively small-scale trials.

Depth-sensing cameras, such as the Kinect sensor (Microsoft™, USA), may offer an affordable and pragmatic alternative (Dutta, 2012). The Kinect sensor allows depth and infrared images (640 by 480 pixels) to be collected simultaneously at 30 Hz with each pixel representing about 0.09 degrees in the image plane. The depth data, with an error ranging from less than 0.2 mm at small (0.4 m) distances to 4 cm at large distances (5 m) (Khoshelham & Elberink, 2012), are more precise than the better known skeletal tracking data (Dutta, 2012). These depth arrays are currently being used in a range of disciplines and recently in biomechanics research to measure foot kinematics (van den Herrewegen et al., 2014).

The aim of this study is to develop and evaluate the use of a single-camera system, based on this technology, to quantify the 3-dimensional kinematics of the pelvic and trunk regions during treadmill locomotion.

2. Methods

Nine male participants volunteered for the study (age 29.2 ± 4.2 y, height 182.9 ± 7.3 cm, mass 84.5 ± 10.4 kg and body mass index 25.3 ± 3.1 kg/m^2). The participants had no prior or existing lower limb injury or neurological disorder affecting gait. Ethical approval was obtained from Teesside University and written informed consent was obtained from all participants. Participants attended the laboratory on two occasions. First, they undertook the 30-15 Intermittent Fitness Test (30-15 IFT) (Buchheit, 2005) which allowed the determination of appropriate running speeds for the experimental trial by recording the maximum running velocity reached at the end of the test (VIFT). On the second visit, participants completed trials (180s each) at 3 different speeds of locomotion which were: walking at self-selected speed (3.6-5.6 km/h), running at 70% of VIFT (10.9-14.0 km/h) and running at 90% of VIFT (14.0-18.0 km/h).

The depth-sensing camera (Kinect™ for Windows, Version 1, Microsoft, USA) projects a structured grid of infrared light into the field of view. The system is pre-programmed to triangulate the reflections of this grid in order to determine camera-object distances on a pixel-by-pixel basis. Our algorithm for 3-dimensional measurement involved the creation of a point cloud around the region of interest. In this example, retro-reflective markers (Figure 1a) were used to create overexposed effects on the infrared image (Figure 1bi), thus allowing marker centroids to be determined on a frame-by-frame basis using standard threshold procedures. Starting five pixels above the centroid, four scanlines (two vertical and two horizontal) were superimposed on the depth image (Figure 1bi). The depth data along these scanlines were then used to create a 42 point cloud around each marker (Figure 1bii, iii and iv) with the mean depth being used as the camera-marker distance (Z_L [Figure 1a]). Using trigonometry and field of view information supplied by the manufacturer (43 degrees vertical and 57 degrees horizontal), the medial-lateral (X_L) and superior-inferior (Z_L) positions of the marker were calculated for all markers. The tracked data from the single-camera system was to be compared with concurrently collected data from a commercially available six-camera motion capture solution (Vicon MX13 and Vicon Nexus 1.7, Vicon Motion Systems, UK). The six-camera system is a passive video based 3D motion capture system which was calibrated prior to every session, following manufacturers' guidelines, to ensure image error was below 0.18 mm.

In order to run both systems concurrently for the treadmill trials some compromises on the quality of the angular data had to be made. Notably, a commonly accepted model for the 3-dimensional kinematics of the pelvis (e.g. Kadaba et al. 1990) was not feasible due to occlusion of the anterior markers by the arms, adipose tissue and the treadmill safety guard. An alternative approach using a posteriorly positioned cluster of orthogonally positioned markers (Borhani et al., 2013) was tested but our tracking algorithm lacked the elegance to separate very closely-positioned markers. Subsequently, we therefore had to compromise on quality of the data by using just two markers (30 mm in diameter) on each of the posterior iliac spines and on each of the tenth ribs (Figure 1a). For both systems, the linear positions of the pelvis and trunk were defined as the mid-points of the vectors joining left- and right-sided markers. Angular positions were recorded as the angles these vectors made relative to the X-axis when projected onto the global XY and XZ planes (Figure 1a). These measures are proxy measures of rotation and obliquity, respectively. Unfortunately, it was not possible to derive measures of pelvic tilt (i.e. sagittal plane movements) or Euler angles as suggested by Wu et al. (2002). This approach did, however, allow us to assess the potential of this simple device for deriving angular data in addition to linear data.

Sampling frequency for the six-camera system was 100Hz and data from the single-camera (approximately 30Hz) were upsampled to 100Hz using linear interpolation. Cameras for the six-camera system were set at a height of 1.9 m. The height of the single-camera was 1.6 m (i.e. approximately the same level of the participants' posterior-superior iliac spines when standing on the treadmill). The distance between the single-camera system and the participant was between 1.0-3.6 m to ensure the highest quality field of view while maintaining accuracy (Dutta, 2012). For comparison purposes, an angular (+90°, +180°, 0°) and linear transformation using the position of the single-camera in the global frame were applied to the data from the single camera system. The time-series over a 10 second period for the triaxial linear (Figure 2a, b and c) and biplanar angular (Figure 2d and e) data were used to determine the range-of-movements (ROM) on a stride-by-stride basis. Specifically, the beginning of a gait cycle was identified at every 2nd point of inflexion on the superior-inferior time-series for the pelvis (Figure 2b).

A within-subject design (Weston et al., 2014) was used to determine the association between the ROM data for the single- and six-camera systems. This design permits the analysis of within-subject changes by removing between-subject differences (Bland and Altman, 1995). Confidence limits (90%) for the within-subject correlations were calculated as per Altman and Bland (2011). The following scale of magnitudes was used to interpret the magnitude of the correlation coefficients: <0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; >0.9, nearly perfect (Hopkins et al., 2009). Limits of Agreement (LoA) (Bland and Altman, 1986) were also used to assess the agreement between the single- and six-camera systems. This method allows for the systematic and random error to be analysed between the two systems (Giavarina, 2015).

3. Results

All within subject correlations for the single- and six-camera systems are displayed in Table 1. Within subject correlations for the association between the single- and six-camera systems when examining the linear ROM of the pelvis were nearly perfect for all directions and speeds with the exception of the ROMs recorded in the anterior-posterior direction at the fastest speed, which was very large (r = 0.89, 90% Confidence Limit: 0.76-0.96). Similarly, nearly perfect correlations were found for the trunk with the exceptions of anterior-posterior movements when running at 70% of VIFT (r=0.90, CL: 0.76-0.96) and 90% of VIFT (r = 0.87, CL: 0.71-0.95). The correlations between the two systems in terms of angular ROMs were less consistent ranging from moderate to large at self-selected walking and large to very large when running. The agreement between the two systems (Table 2) for linear movements is ≤ 9.9 mm at all velocities of gait and ≤ 4.6 degrees at all velocities of gait. Descriptive data for the absolute linear and angular ROM for both systems are presented in Table 3.

4. Discussion

This study is based on the premise that kinematic data of the pelvis and trunk could contribute to injury management and may facilitate gait retraining (e.g. Sharma et al., 2014; Crowell and Davis, 2011). To do so, requires a prospective study which in turn requires a system which is safe, rapid, easy-to-use and portable. The single-camera system described in this study meets these requirements and the data it produces compares reasonably well with the six-camera system for the degrees of freedoms tested. In addition, the absolute values reported are comparable with previous literature. Superior-inferior and medial-lateral movements of the pelvis (mean ROM 4.7 cm and 5.0 cm, respectively) during walking were within the ranges (2.5–9.5 cm and 2.0–6.0 cm) reported by Thorstensson et al. (1982), although the anterior-posterior movements (3.9 cm) were slightly higher. Transversal pelvic rotations during walking (6.3 ±1.8 degrees) match those reported by Staszkiewicz et al. (2012) (6.3 ± 2.5 degrees) for treadmill walking at 5 km/h. Similarly transversal pelvic rotations during running (9.3 ± 2.1 degrees) were within the range reported in previous studies (Kadaba et al., 1990; Saunders et al., 2005). Consistent with previous studies (Saunders et al., 2005 and Crosbie et al., 1997), the data from the two systems showed increases in ROM of the pelvic and trunk motion in all planes with an increase in walking and running speed. Taken together this practical system may provide a useful tool for the objective assessment of the pelvis and trunk during treadmill locomotion.

There are important limitations with the current system and also with the research design. Despite reasonable agreement between the two systems in terms of angular ROM, it should be reiterated that the variables being reported here are necessarily simplified and do not meet the accepted standards (Wu et al., 2002). To address this shortfall in future will require additional markers, which in turn will necessitate improved tracking algorithms and/or additional sensors (*e.g*. Buganè et al., 2014). In order to ensure that intra-marker distances remain sufficient to avoid accentuating angular error it may be necessary to find new marker locations or improved versions of the camera (i.e. with a higher resolution). Secondly, it should also be noted that the single-camera system described in this study has been created specifically for the analysis of upright treadmill locomotion and thus could not be used for more complex movements. Thirdly, our sample was fairly homogeneous in terms of anthropometric variables and the system would need to be tested in a wider population which may include clinical or obese populations, for whom small abnormal movements and skin movements may be much more problematic (Schache et al., 2002b). Nonetheless, the posterior approach to measurement, as used in this system, appears to be more reliable than traditional kinematic models for these populations (Borhani et al., 2013).

In conclusion, this study has shown that the single depth-sensing camera system offers a pragmatic method for kinematic capture of the pelvic and trunk regions for most of the degrees of freedom tested. However, further research to address the highlighted limitations is recommended before being used for large-scale data collection and biofeedback applications.

Conflict of interest statement

None of the authors have a conflict of interest related to this work.

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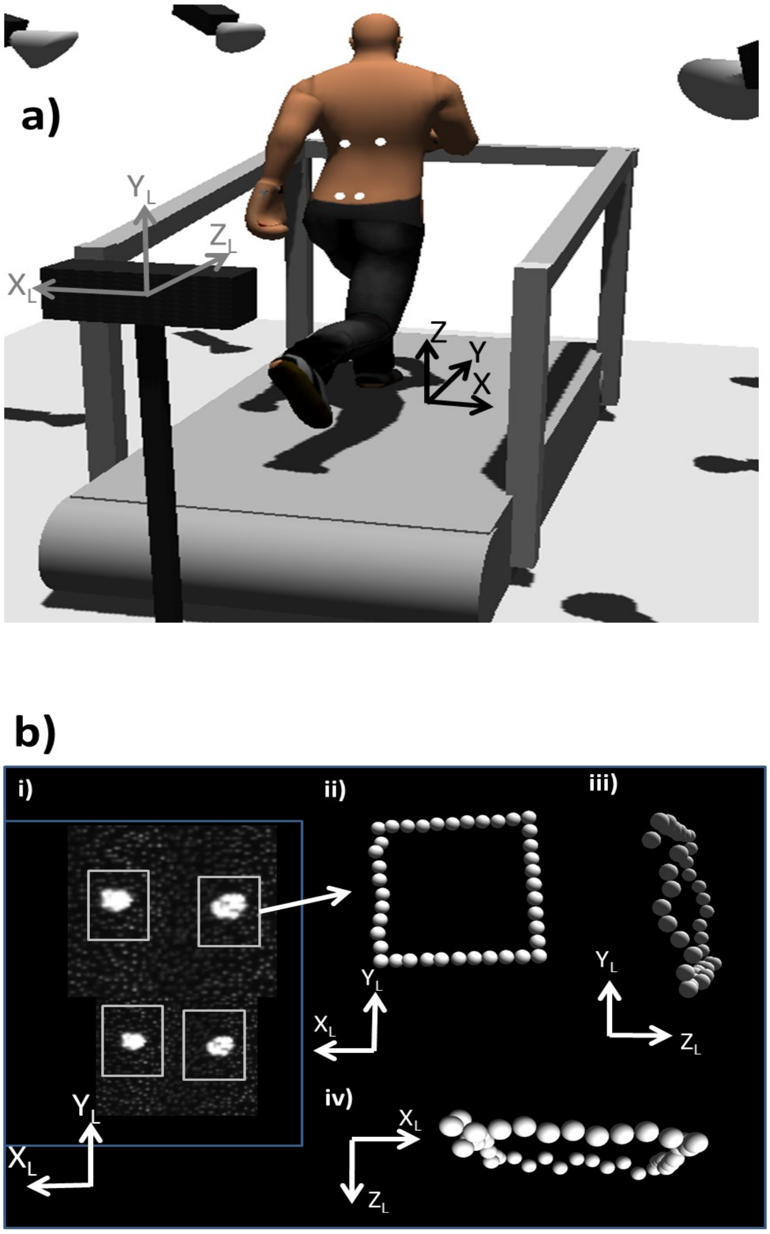

Figure 1. The steps taken to collect data.

a) A stationary treadmill was positioned in the six-camera motion capture laboratory. The six cameras were positioned 3m apart surrounding the action. At the rear of the treadmill was the single depth-sensing camera positioned 1.6m above the floor and pointing towards the participant's posterior pelvic region. The participant was fitted with four retro-reflective markers located on the iliac spines and tenth ribs. Also shown are the coordinate systems (right-hand-rule) of the single camera system in grey (X_L,Y_L and Z_L) and the six-camera-system in black (X,Y and Z).

b) The resulting infrared image of the 4 markers (i) showing the overexposed pixels and the scanlines used to create the 3-dimensional point cloud around the perimeter of the marker. The resulting point cloud shown from the posterior (ii), lateral (iii) and superior (iv) views. Also shown is the orientation of single-camera local system.

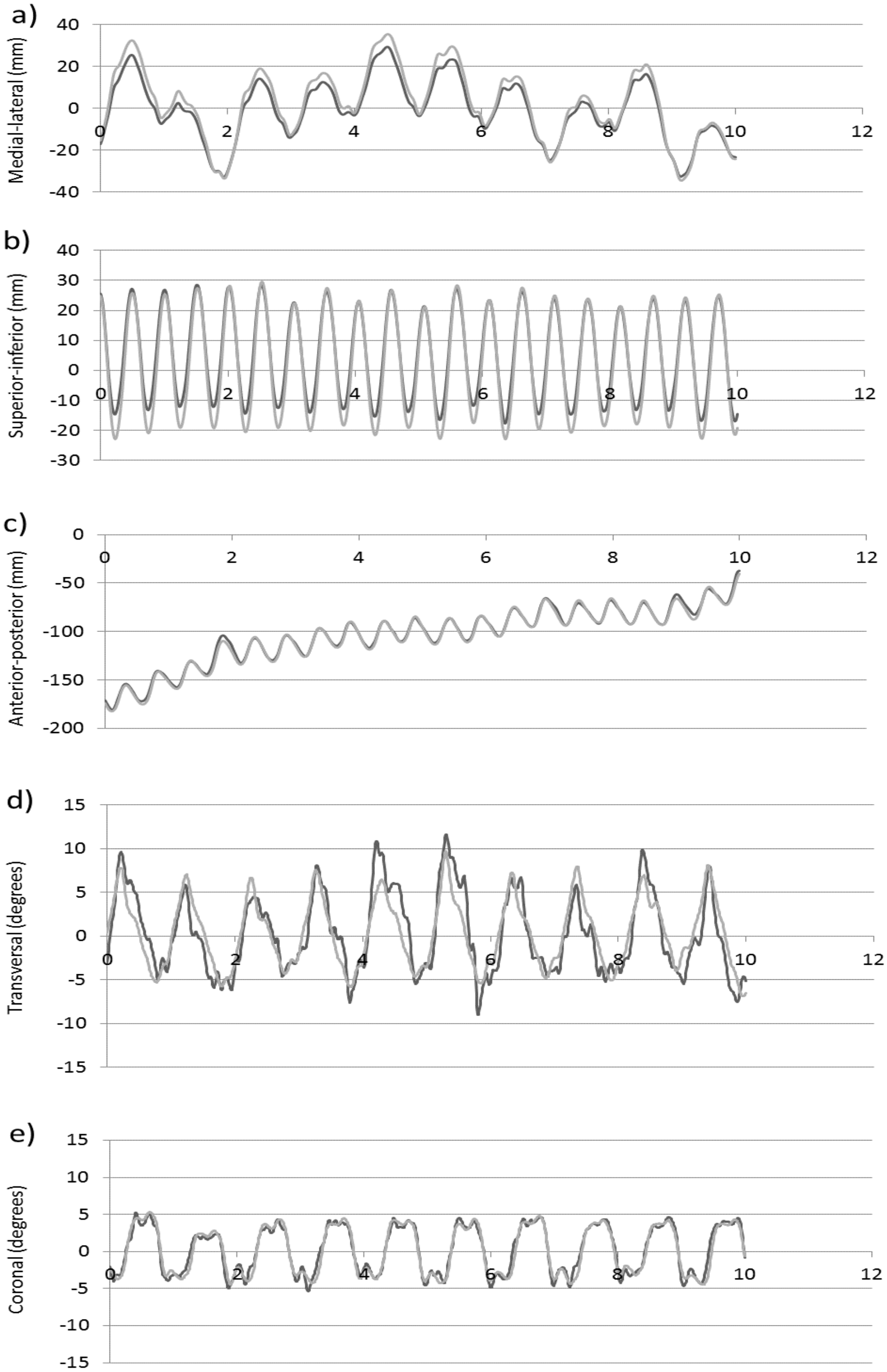

Figure 2. Time-series of data points taken over a 10 second interval for self-selected walking in the pelvis of one of the participants. The single depth-sensing camera (black line) and the six-camera system (grey line). Positional data in the medial-lateral (a), superior-inferior (b) and anterior-posterior directions (c). Angular rotations are in the transversal (d) and coronal (e) planes.

Table 1. Within subject correlation coefficients between the six- and one-camera systems, reported with 90% Confidence Limits and the magnitude of correlation coefficient descriptor.

	Linear						***Angular***			
	Pelvis			Trunk			Pelvis		Trunk	
	Medial-lateral	Anterior-posterior	Superior-inferior	Medial-lateral	Anterior-posterior	Superior-inferior	Frontal	Transversal	Frontal	Transversal
Walking	0.97 (0.93-0.99) *Nearly Perfect*	0.96 (0.91-0.99) *Nearly Perfect*	0.92 (0.82-0.97) *Nearly Perfect*	0.99 (0.96-1.00) *Nearly Perfect*	0.91 (0.79-0.96) *Nearly Perfect*	0.88 (0.73-0.95) *Very Large*	0.41 (0.02-0.69) *Moderate*	0.41 (0.03-0.69) *Moderate*	0.57 (0.23-0.79) *Large*	0.66 (0.36-0.84) *Large*
70% VIFT	0.98 (0.96-0.99) *Nearly Perfect*	0.91 (0.78-0.96) *Nearly Perfect*	0.99 (0.96-1.00) *Nearly Perfect*	0.99 (0.98-1.00) *Nearly Perfect*	0.90 (0.76-0.96) *Very Large*	0.98 (0.96-0.99) *Nearly Perfect*	0.53 (0.17-0.76) *Large*	0.62 (0.29-0.81) *Large*	0.73 (0.47-0.88) *Very Large*	0.75 (0.50-0.89) *Very Large*
90% VIFT	0.99 (0.98-1.00) *Nearly Perfect*	0.89 (0.76-0.96) *Very Large*	0.95 (0.88-0.98) *Nearly Perfect*	1.00 (0.99-1.00) *Nearly Perfect*	0.87 (0.71-0.95) *Very Large*	0.99 (0.96-1.00) *Nearly Perfect*	0.61 (0.28-0.81) *Large*	0.59 (0.25-0.80) *Large*	0.80 (0.58-0.91) *Very Large*	0.79 (0.57-0.91) *Very Large*

Table 2. Limits of Agreement between the single- and six-camera systems for linear (mm) and angular (degrees) movements (Bias ± 95% Confidence Intervals)

	Linear (mm)						***Angular (degrees)***			
	Pelvis			Trunk			Pelvis		Trunk	
	Medial-lateral	Anterior-posterior	Superior-inferior	Medial-lateral	Anterior-posterior	Superior-inferior	Frontal	Transversal	Frontal	Transversal
Walking	-2.0 ± 1.6	-0.8 ± 3.9	-3.2 ± 1.9	-2.1 ± 1.3	-1.0 ± 5.0	-3.6 ± 1.9	-1.1 ± 2.2	-1.5 ± 1.2	-4.6 ± 5.9	-2.2 ± 4.9
70% VIFT	-2.5 ± 1.7	-3.4 ± 6.4	-7.9 ± 3.0	-3.3 ± 2.3	-9.4 ± 7.8	-5.4 ± 3.0	-1.6 ± 1.7	-1.1 ± 1.4	-3.2 ± 6.5	-0.3 ± 5.7
90% VIFT	-3.2 ± 2.7	-3.7 ± 7.9	-7.7 ± 2.3	-3.5 ± 2.0	-9.9 ± 8.5	-5.6 ± 2.3	-1.3 ± 1.5	-1.1 ± 1.2	-2.2 ± 5.9	-0.8 ± 5.3

Table 3. Absolute linear (mm) and angular amplitudes (degrees) for the single-camera systems (Mean ± Standard Deviation)

	Linear						***Angular***			
	Pelvis			Trunk			Pelvis		Trunk	
	Medial-lateral	Anterior-posterior	Superior-inferior	Medial-lateral	Anterior-posterior	Superior-inferior	Frontal	Transversal	Frontal	Transversal
Walking	50.4±15.7	39.3±8.2	46.8±9.8	55.6±19.3	35.0±7.0	48.7±8.5	10.5±1.1	6.3±1.8	15.7±3.9	9.9±2.1
70% VIFT	38.6±11.0	44.6±6.6	106.7±12.7	68.0±15.8	44.1±7.8	90.6±9.6	11.6±2.1	9.3±2.1	15.4±3.4	23.5±6.0
90% VIFT	50.4±12.1	44.7±5.7	99.7±12.6	75.5±16.9	43.3±8.2	84.9±10.5	12.0±2.1	9.4±2.2	17.5±3.8	26.9±5.9

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